Executive Summary

Acceleration limits are set in the x, y, and z axes for all mission phases to protect the crew from injury and other acceleration-related conditions. These limits are divided into two-time regimes:

- sustained (>0.5 seconds), and
- transient (≤0.5 seconds)

They are further divided according to:

- whether the acceleration is translational or rotational
- the phase of flight, and
- whether the crew is standing or sitting

Several countermeasures can be used to mitigate the effects of high acceleration loads. Additional factors such as parachute sway and seat angle need to be considered when assessing risk and developing solutions.

Relevant Standards

NASA-STD-3001 Volume 2, Rev C

[V2 6064] Sustained Translational Acceleration Limits

[V2 6065] Rotational Velocity

[V2 6066] Sustained Rotational Acceleration Due to Cross-Coupled Rotation

[V2 6067] Transient Rotational Acceleration

[V2 6069] Acceleration Injury Prevention

[V2 6070] Injury Risk Criterion

[V2 6111] Dynamic Mission Phases Monitoring and Analysis

SpaceX Crew Dragon Launch

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Background & Reference Data

Basis of current limits:
- Sustained: prior crewed vehicle data; human tolerance limits
- Transient: Apollo lunar landing impact data; Shuttle & International Space Station (ISS) post-flight crew jump data; ISS inflight treadmill foot strike data

The Brinkley Dynamic Response Model
- Dynamic Response (DR)
    - Estimates the **transient** acceleration of the human body
    - A single degree of freedom lumped mass model
    - Calculated independently in each direction
    - Responses are highly specific for seat used in development
        - Changes to the seat, restraints and helmet can invalidate the model natural frequency and damping coefficient
        - Ground rules established to ensure model is valid to use
- Injury Risk Criterion (β)
    - Preset DR limits in each direction estimate the injury risk
    - Estimates an injury risk but not severity or anatomical location
- Limitations
    - Subject pool limited to mostly young, male military volunteers
    - DR Limits based on limited statistical analysis of injury data
   - Limited validity in +X, -Z and ±Y axes

Note: Information applicable to all axes

The 50% probability (P) of injury for +z axis is based on an *n* greater than 100, yielding 95% confidence interval (P=0.5, *n*=100) is 0.402 ≤ P ≤ 0.598. Where P=0.11 and *n*=89, the 95% confidence interval is 0.045 ≤ P ≤ 0.175. The confidence intervals for the +z axis means become smaller for lower risk values (5% and lower).

Table 6.5-8 Approximate Risk Values for the Brinkley Model

Category	Approximate Risk
Low	0.5%
Medium	5.0%
High	50%

From: NASA/TM-2013-217380
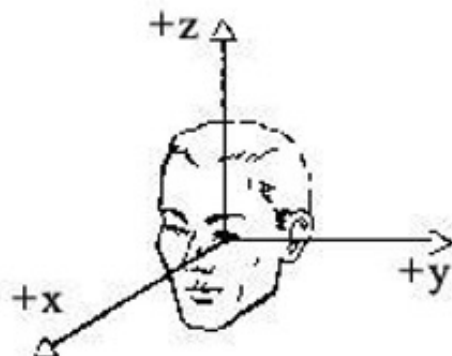
For information on how to use this model, see NASA/TM-2013-217380, Revision 1, Application of the Brinkley Dynamic Response Criterion to Spacecraft Transient Dynamic Events.

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Background & Reference Data

## Health and Performance Risks of Excessive Acceleration Exposure

Sustained
- Limited/difficulty of movement & breathing; unconsciousness
- See Standard [V2 6064] in NASA-STD-3001 Volume 2, Rev C for limits
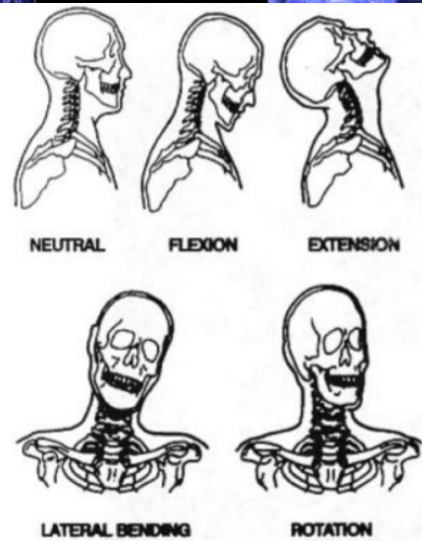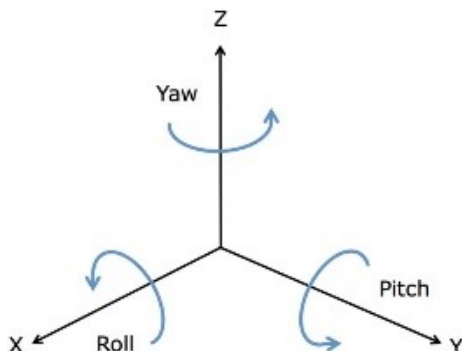- Reference Human Integration Design Handbook (HIDH) Table 6.5-3

Transient
- Mostly traumatic injuries
- Vertebral injuries most common
- See Standard [V2 6069] in NASA-STD-3001 Volume 2, Rev C for limits
- Reference HIDH Section 6.5.3.2
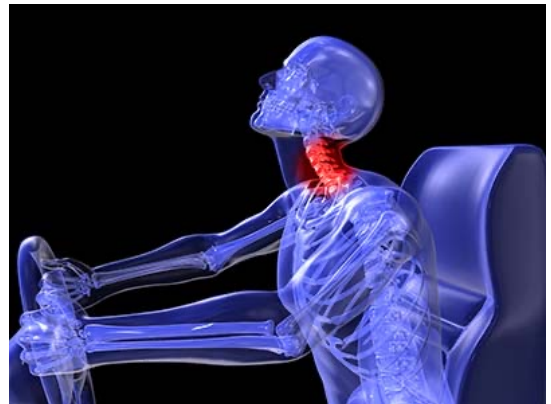
Rotational
- Disorientation; sickness; unconsciousness
- See Standard [V2 6066] & [V2 6067] in NASA-STD-3001 Volume 2, Rev C for limits
- Reference HIDH Table 6.5-9

NEUTRAL   FLEXION   EXTENSION

LATERAL BENDING   ROTATION

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Design Guidance

- Assumptions of the standing limits given in the requirements:
    - Additional equipment (suit) mass borne by the crewmember is <20% of the crewmember's shirtsleeve mass
    - Adequate restraint(s) are provided for all body postures
- Cross-discipline considerations
    - Critical to consider suit design and mass
    - Hard points on suit can cause injury during transient loads (landing)
    - Space between a crewmember and their suit, as well as the suit and the vehicle habitat, may cause physical harm
- Vibration & acceleration during dynamic phases of flight
    - If a crewmember is already experiencing high G loads (and subsequently limited movement), the effects of vibration on performance may be increased
- Potential countermeasures to orthostatic intolerance while standing
    - Physical/Vehicle (e.g., suit weight or bodyweight offloading, restraint systems)
    - Suit (e.g., anti-g suit, lower body compression)
    - Physiological (e.g., scheduled muscle contractions; breathing exercises; fluid loading and salt tablets)
    - All countermeasures should work concurrently to reduce risk and harm to the crew
- Considerations to meet transient and sustained loads requirements
    - Restraint systems during transition from microgravity
    - Offloading of suit mass that still enables crew performance
    - The suit, vehicle, and restraint systems must all interact conjointly to protect the crew from all types of acceleration loads
    - Seat design along with load attenuation is a critical design element that mitigates loads imparted to the crewmember.
- Mission elapsed time: total time from launch until the acceleration load occurs.

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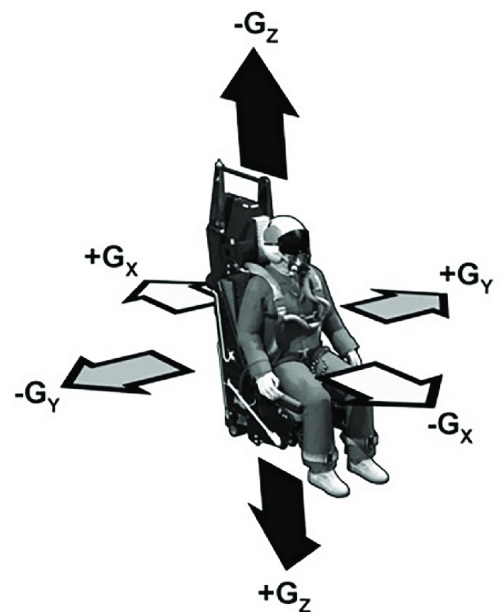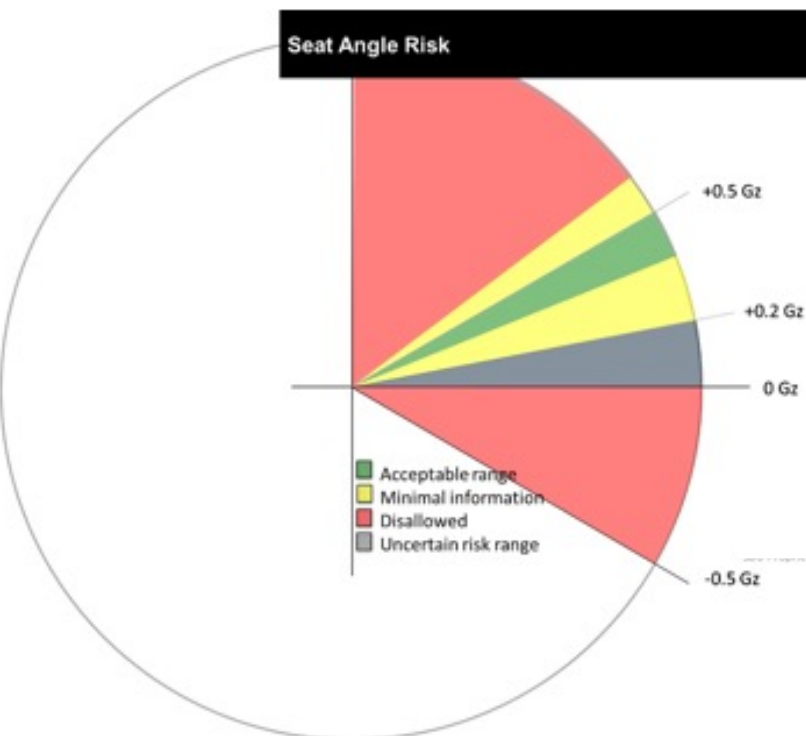
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Design Guidance

Seat Angle

For impact tolerance, the +Gx orientation is the most advantageous direction of loading. In this orientation, humans can withstand much higher accelerations (by a factor of >2) than in other vectors. However, unless a vehicle lands with a zero downrange velocity, the landing impact will not be purely confined to a single axis. The +Gz orientation is most advantageous as the secondary impact vector due to increased tolerance and greater model fidelity in predicting injury.

In a vehicle with no roll control, any direction of impact is equally likely. In each vehicle case, an extensive assessment of nominal, off-nominal and contingency conditions would be necessary to accurately assess the risk to the crew due to impact. Depending on the direction of impact, different seat angles could either increase or decrease the risk of injury. A combination of roll control and a seat configuration that ensures a +Gx and +Gz impact is preferred.
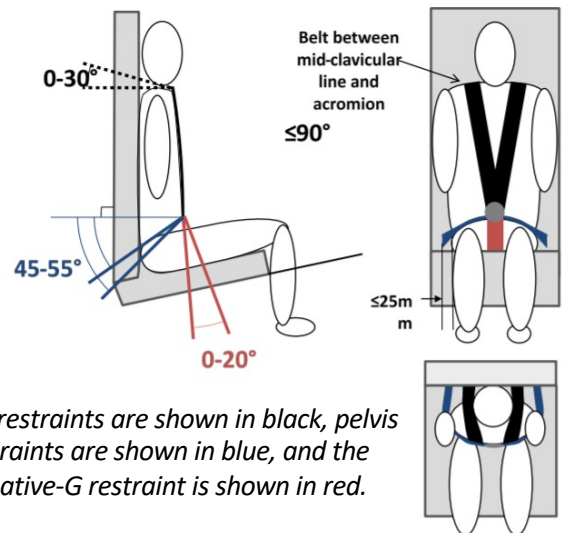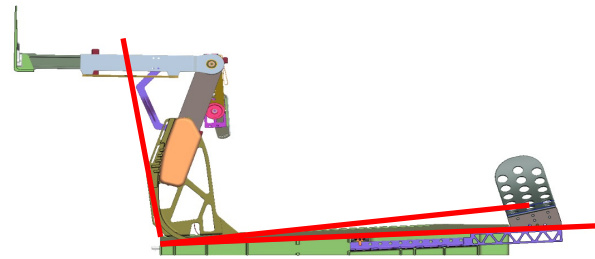
Torso restraints are shown in black, pelvis restraints are shown in blue, and the negative-G restraint is shown in red.

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Application Notes

Parachute Sway

As a capsule returns to earth with parachutes deployed, it is prone to swaying back and forth in the wind. Not only does this affect the angle of impact (by up to 24.5⁰), but velocity of impact. The capsule will fall slower or faster depending on the angular position of the sway.

Figure 1. Pendulum motion under two Mains observed from chase helicopter during CDT-3-12.
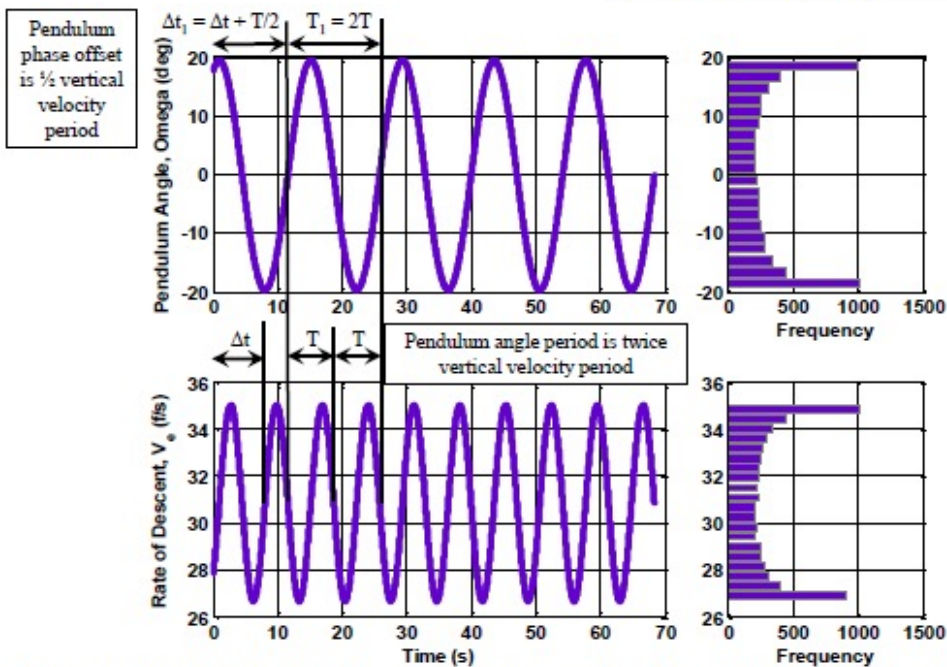
Figure 4. Relationship between pendulum swing angle and vertical velocity component.

Shortening parachute riser length to reduce the distance between the parachute and payload has been shown to mitigate sway during descent. Additionally, an Over-Inflation Control Line reduces swing amplification by restricting the canopy diameter.

Reference: AIAA 2015-2138, Pendulum Motion in Main Parachute Clusters, Ray & Machin, April 2015

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Back-Up

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Major Changes Between Revisions

Original → Rev A

- Updated information to be consistent with NASA-STD-3001 Volume 1 Rev B and Volume 2 Rev C.

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Referenced Standards

NASA-STD-3001 Volume 2 Revision C

[V2 6064] Sustained Translational Acceleration Limits The system shall limit the magnitude, direction, and duration of crew exposure to sustained (>0.5 seconds) translational acceleration by staying below the limits in Figure 4—Gx Sustained Translational Acceleration Limits (Seated), Figure 5—Gy Sustained Translational Acceleration Limits (Seated), and Figure 6—Gz Sustained Translational Acceleration Limits (Seated) for seated posture, and Figure 7—Gx Sustained Translational Acceleration Limits (Standing), Figure 8—Gy Sustained Translational Acceleration Limits (Standing), and Figure 9—Gz Sustained Translational Acceleration Limits (Standing) for standing posture.

[V2 6065] Rotational Velocity The system shall limit crew exposure to rotational velocities in yaw, pitch, and roll by staying below the limits specified in Figure 9—Rotational Velocity Limits.

[V2 6066] Sustained Rotational Acceleration Due to Cross-Coupled Rotation The system shall prevent the crew exposure to sustained (>0.5 second) rotational accelerations caused by cross-coupled rotations greater than 2 rad/s^2.

[V2 6067] Transient Rotational Acceleration The system shall limit transient (≤0.5 seconds) rotational accelerations in yaw, pitch, or roll to which the crew is exposed and the limit used appropriately scaled for each crewmember size from the 50th percentile male limits of 2,200 rad/s^2 for nominal and 3,800 rad/s^2 for off-nominal cases.

[V2 6069] Acceleration Injury Prevention The system shall mitigate the risk of injury to crewmembers caused by accelerations during dynamic mission phases per Table 5, Acceptable Injury Risk Due to Dynamic Loads.

[V2 6070] Injury Risk Criterion The system shall limit crew exposure to transient translational acceleration (≤0.5 seconds) by limiting the injury risk criterion (β/beta) to no greater than 1.0 (Low) for seated or standing crew as defined by Dynamic Response (DR) limits in NASA/TM-20205008198 Table 2 "Updated Dynamic Response Limits for Standing", while crew are restrained as required in NASA/TM-2013-217380REV1 for seated crew, or NASA/TM – 20205008198 for standing crew.

[V2 6111] Dynamic Mission Phases Monitoring and Analysis The system shall collect vehicle and crewmember acceleration parameters, specific kinematic responses, and associated metadata, during all dynamic mission phases and suited operations (defined as ascent, abort, entry, descent, landing, postlanding, and EVA operations)to correlate with any injuries incurred by crewmembers.

All referenced tables and figures are available in NASA-STD-3001, Volume 2

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2. Human Integration Design Handbook (HIDH). (2014). NASA/SP-2010-3407/REV1. https://www.nasa.gov/sites/default/files/atoms/files/human_integration_design_handbook_revision_1.pdf

3. Somers, J.T., Gohmert, D., & Brinkley, J.W. (2017). Application of the Brinkley Dynamic Response Criterion to Spacecraft Transient Dynamic Events. NASA/TM-2013-217380-REV1. https://ntrs.nasa.gov/api/citations/20170005913/downloads/20170005913.pdf

4. Ray, E.S., & Machin, R.A. (2015). Pendulum Motion in Main Parachute Clusters.. *Aerodynamic Decelerator Systems Technology Conferences.* https://eric.mnray.net/data/cpas/AIAA-2015-2138_Pendulum.pdf

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